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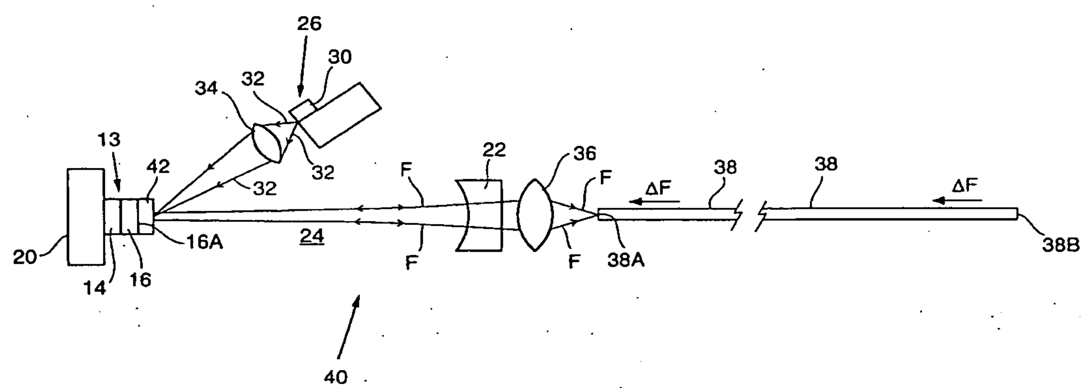
(54) Title: OPTICALLY-PUMPED SEMICONDUCTOR LASER WITH OUTPUT COUPLED TO OPTICAL FIBER



(57) Abstract: A laser system includes an optically-pumped semiconductor laser OPS-laser and an optical fiber. Output radiation from the OPS laser is coupled into an input end of an optical fiber for transporting the output radiation to a delivery location. The OPS-laser includes an optical arrangement for minimizing mode-noise resulting from feedback into the OPS laser of a portion of the radiation which is reflected from an output end of the optical fiber.

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OPTICALLY-PUMPED SEMICONDUCTOR LASER WITH OUTPUT COUPLED TO OPTICAL FIBER

TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to external-cavity semiconductor lasers. It relates in particular to external-cavity, optically-pumped, surface-emitting semiconductor lasers (OPS-lasers) the output of which is coupled to an optical fiber.

DISCUSSION OF BACKGROUND ART

OPS-lasers are capable of providing a high-quality monochromatic beam of optical radiation in a wide range of wavelengths. The wavelength of fundamental radiation generated by an OPS laser is determined, inter alia, by the composition of active layers in a multilayer semiconductor gain-structure arranged to provide optical gain when optically-pumped.

Within certain wavelength ranges characteristic of the general composition of the semiconductor material of the active layers, i.e, the combination of elements in the material, the wavelength may be essentially continuously varied by adjusting the relative amounts of elements in the material. Ranges of available wavelengths may be extended by including one or more optically-nonlinear crystals inside or outside an OPS laser resonator to convert the fundamental wavelength to another wavelength, for example, the second, third, or fourth harmonic wavelength.

Active layers in an OPS-laser gain-structure are separated by spacer layers which absorb the wavelength of light used to optically pump the gain

structure. Spacer layers are arranged such that the active layers are optically spaced apart by about one half-wavelength at the fundamental wavelength. An OPS-laser resonator design in which this gain-structure is located at the end of the resonator can be readily made to deliver radiation in a single axial mode. Running in a single axial mode provides for a high-quality beam which can be focused into a very small (essentially diffraction limited) spot. Single-mode operation is also preferred when the OPS-laser radiation is used to transmit information along an optical fiber, for example in telecommunication applications.

A problem has been discovered, however, in that when radiation from an OPS laser is focused into an optical fiber for transmission thereby, a portion of the radiation is reflected (fed) back from the delivery end of the optical fiber into the OPS-laser resonator. A result of this unwanted feedback is that the oscillation of the resonator is caused to repeatedly switch from oscillating in one possible mode to another. This causes fluctuation or mode-noise in the output of the OPS-laser. Accordingly, there is a need for a single-mode OPS-laser resonator arrangement for focusing radiation into an optical fiber which is unaffected by feedback from the optical-fiber.

SUMMARY OF THE INVENTION

The present invention is directed to an OPS-laser having a low-noise output. In one aspect, an OPS laser in accordance with the present invention comprises a monolithic multilayer OPS-structure including a semiconductor multilayer surface-emitting gain-structure having an emitting surface. The gain-structure includes a plurality of active layers

spaced-apart by spacer layers and arranged to provide optical gain in the laser resonant-cavity. The optical gain occurs within a gain bandwidth characteristic of the composition of the gain-structure. The OPS laser has a resonant-cavity terminated by first and second mirrors. The laser resonant-cavity is configured to include the gain-structure of the OPS-structure. A pump-radiation source is arranged to deliver pump-radiation to the gain-structure for generating laser-radiation in the laser resonant-cavity. The OPS laser includes an optical arrangement for selecting a frequency of the laser-radiation within the gain bandwidth of said gain-structure.

In another aspect of the present invention, output of the OPS-laser is coupled into a optical fiber for transport or delivery to a site or device in which it will be used. The output is focussed into an input end of the optical fiber by a lens or the like and is delivered from an output end of the optical fiber. In the absence of the frequency-selective optical arrangement, coupling into the optical fiber can cause mode noise in the OPS-laser output. This mode noise results, inter alia, from reflective feedback of a portion of the OPS-laser output back into the OPS-laser from a delivery end of the optical fiber. The frequency selective optical arrangement is configured to minimize this mode noise.

A preferred frequency selective arrangement includes providing that the emitting surface of the gain-structure is sufficiently reflective that the gain-structure behaves as an etalon. This can be effected by leaving an outermost layer of the gain-structure uncoated such that the Fresnel reflection

of the material of the outermost layer provides the desired reflectivity. Alternatively, the reflectivity of the emitting surface can be increased above the Fresnel value by depositing a reflective, multilayer interference coating thereon.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, schematically illustrate a preferred embodiment of the present invention, and together with the general description given above and the detailed description of the preferred embodiment given below, serve to explain the principles of the invention.

FIG. 1 schematically illustrates a prior art optically-pumped, external-cavity surface-emitting semiconductor laser (OPS-laser) arranged deliver radiation therefrom into an optical fiber.

FIG. 2 is a graph schematically illustrating possible modes of oscillation of the laser of FIG. 1

FIG. 3 is a graph schematically illustrating the effect of reflective feedback from the optical-fiber of FIG. 1 on the possible modes of oscillation of the laser of FIG. 1.

FIG. 4 schematically illustrates one preferred embodiment of an optically-pumped, external-cavity surface-emitting semiconductor laser in accordance with the present invention arranged deliver radiation therefrom into an optical fiber and including a semiconductor multilayer gain-structure having a

partially transmitting mirror on an emitting surface thereof for suppressing the effect of the reflective feedback from the optical fiber.

FIG. 5 is a graph schematically illustrating the effect of the partially transmitting mirror on the gain structure of FIG. 4 on the reflective-feedback effect of FIG. 2.

FIG. 6 is a graph schematically illustrating the number of possible modes of oscillation of the laser of FIG. 4 as a function of the magnitude of reflective feedback and the reflectivity of the partially transmitting mirror on the gain structure of FIG. 4.

FIGS 7A-C schematically illustrate arrangements for providing the partially transmitting mirror on the emitting surface of the gain structure of FIG. 4.

FIG. 8 schematically illustrates another preferred embodiment of an optically-pumped, external-cavity surface-emitting semiconductor laser in accordance with the present invention arranged deliver radiation therefrom into an optical fiber and including an intra-resonator semiconductor multilayer gain-structure having an uncoated emitting surface thereof forming a partially transmitting mirror thereon and including a birefringent filter.

DETAILED DESCRIPTION OF THE INVENTION

Before presenting a detailed description of an OPS laser in accordance with the present invention it is useful to briefly review the arrangement of a prior-art single-mode OPS-laser delivering radiation into an optical fiber. Turning to the drawings,

wherein like components are designated by like reference numerals, FIG. 1 depicts a prior-art OPS-laser 10 arranged to deliver fundamental radiation in a single axial-mode. Laser 10 includes a monolithic (surface-emitting) multilayer structure (OPS-structure) 12 including a Bragg-mirror structure 14, and a gain-structure 16 including a plurality of active layers (not shown) spaced apart by spacer-layers (not shown). An antireflection coating 18 is deposited on emitting surface 16A of gain structure 16. OPS-structure 12 is in thermal contact with a substrate or heat-sink 20.

An external mirror 22 having a partially-transmitting reflective coating 23 thereon is spaced apart from and aligned with Bragg-mirror structure 14 of OPS-structure 12 to define a laser-resonator 24. Gain-structure 16 of OPS-structure 12 is thereby incorporated in laser-resonator 24.

A pump-radiation source 26 is arranged to deliver pump-radiation to gain-structure 16 of OPS-structure 12, via emitting surface 16A thereof, for generating laser-radiation in laser-resonator 24. Fundamental radiation so generated circulates in laser resonator 24 as indicated by rays F. Pump-radiation source 26 includes an edge-emitting semiconductor diode-laser 30 or an array of such lasers. Pump-radiation 32 from diode-laser 30 is focused by a lens 34 onto gain-structure 16 of OPS-structure 12.

A portion of circulating radiation F is coupled out of laser-resonator 24 via partially transmitting mirror 22 as output-radiation and is focused by a lens 36 into an optical fiber 38 for delivery to a site or apparatus where it will be used.

As discussed above, focussing single axial mode

radiation from laser such as laser 10 into an optical fiber has been found to perturb the otherwise quiet, true single-mode operation of the OPS-laser. This perturbation or output fluctuation may be referred to as mode-noise. One possible explanation of the mechanism of this perturbation and a method for at least minimizing the perturbation, if not eliminating it altogether, is discussed below with reference to FIGS. 2, 3, and 4.

In FIG. 2 is shown the hypothetical transmission as a function of frequency of resonator 24 considered as an etalon. The transmission peaks N, N+1, N+2, N+3 and N+4 represent some of the many possible oscillation (lasing) frequencies (modes) of laser-resonator 24. The frequencies (wavelengths) at which these modes occur are those frequencies for which the laser-resonator is an integer number of half-wavelengths in optical length. All modes have a node at Bragg-mirror structure 14 and at partially-transmitting mirror 22.

Gain-structure 16, depending on active layer composition, emits fundamental radiation in a spectrum (gain-bandwidth) having a width of between about two and four percent of a nominal emitting wavelength about in the center of the spectrum. The frequency (wavelength) separation between modes is very small compared with this gain bandwidth. Accordingly, absent any other factor, all modes have an equal chance of oscillating.

Now, as gain-structure 16 is immediately adjacent Bragg-mirror 14, and active layers of the gain structure are spaced apart by about one-half-wavelength at the nominal emitting wavelength, any one of the possible operating modes will derive its gain from the same narrow, active-layer regions of

the gain structure as any other. Accordingly, when the laser is started, that mode which instantaneously is experiencing the lowest loss begins to oscillate, and takes all of the available gain. This prevents any other mode from oscillating and provides an inherent single-mode oscillating characteristic for laser 10.

Referring now to FIG. 3 and again to FIG. 1, when radiation from laser 10 is focussed into optical fiber 38 and transported therealong, some fraction of the radiation ΔF is reflected from output end 38B of the optical fiber. The reflected radiation exits input-end 38A of the optical fiber and is fed back into laser-resonator 24 (see FIG. 1). Because of this, the system of laser 10 and optical-fiber 38 functions as a compound etalon with a first portion thereof being between mirror 22 and end 38B of optical-fiber 38 and a second portion thereof being laser-resonator 24. If optical fiber 38 is relatively long compared with laser-resonator 24, for example about one-meter long, the first portion of the compound etalon will have the effect of modulating the transmission characteristic of the laser-resonator.

The modulation effect is illustrated in FIG. 3 by curve A. The modulation will have a depth ΔT, which is dependent, inter alia, on the magnitude of the feedback ΔF. It can be seen that under this modulation effect, a mode N+2 experiences maximum loss due the modulation while mode N+4 experiences minimal if any loss. A further complication arises in that, as a result of statistical processes or the like in optical fiber 38, the alignment of the modulation effect (curve A) with the possible oscillating modes continually and randomly changes.

If the modulation depth ΔT is sufficiently large, this can cause laser 10 to continually and rapidly, at random intervals, switch from oscillating in one possible mode to another, not necessarily adjacent, mode. It is believed, without being limited to a particular theory, that this is the source of the mode-noise which has been observed.

Referring now to FIG. 4 one preferred embodiment 40 of a single-mode OPS laser in accordance with the present invention is illustrated. Laser 40 delivers radiation F via a focussing lens 36 into a single-mode optical fiber 38. Laser 40 is similar in most respects to laser 10 of FIG. 1 with the exception of the OPS-structure. In laser 40, an OPS-structure 13 includes a Bragg-mirror structure 14 and a multilayer semiconductor gain-structure 16 as in OPS-structure 12 of laser 10. OPS-structure 13, however, includes multilayer mirror-structure 42 deposited or coated on emitting surface 16A of gain-structure 16. Mirror structure 42 causes the surface reflectivity of emitting surface 16A of gain-structure 16 to increase. Coated surface 16A is still, however, partially transmissive at the fundamental wavelength. Mirror-structure 42, Bragg-mirror structure 14 and gain-structure 16 form, in effect, an etalon, with gain-structure 16 being a multiple-half-wavelength spacer of the etalon. Thus arranged, OPS-structure 13, in addition to providing a gain-structure and a resonator mirror, serves as a wavelength-selective device in laser-resonator 22.

An effect of wavelength selectivity on the number of possible oscillating modes of laser 40 is schematically, graphically depicted in FIG. 5. Here, curve B schematically illustrates a degree of wavelength selectivity imparted to laser-resonator 22

by the inclusion of mirror 42 on gain-structure 16. In effect, the wavelength selectivity adds a deeper, low-frequency modulation to the higher frequency modulation (curve A') resulting from feedback F. It can be seen in this particular example that whatever the alignment of curve A' with the mode frequencies of resonator 22, mode N+2 will always have a higher probability of lasing than any adjacent mode.

It should be noted here that the graphs of FIGS 3 and 5 are not intended to provide accurate representations of the feedback modulation frequency, mode separation, or spectral response of the OPS-structure 13 either in absolute or relative terms. These graphs are presented only to provide a simple pictorial representation of what is believed to be the reason that mode-noise has been observed, and a mechanism for minimizing the mode noise.

An approximate numerical relationship between the magnitude of feedback from optical fiber 38 (depth of feedback modulation) and the reflectivity of surface 16A of gain structure 16 (wavelength selectivity of the OPS-structure)is graphically depicted in nomogram form in FIG. 6. Here, a horizontal axis (X-axis) represents reflection (feedback) from optical fiber 44 in negative decibels (-dB) and a vertical axis (Y-axis) represents the reflectivity of surface 16A in decimal notation (1.0 = 100%). The higher the reflectivity of mirror structure 46, the greater the wavelength selectivity of OPS structure 13. The greater the negative dB value of the feedback, the less the feedback.

It is assumed in generating the nomogram of FIG. 6 that the reflectivity of Bragg-mirror structure 14 is greater than 0.99 and is a plane reflector; gain-structure 16 has an optical thickness of fourteen

half wavelengths at the fundamental wavelength; laser-resonator 24 has a length of 35.0 mm; and mirror 20 has a radius of curvature of 50.0 mm and a reflectivity of 98%. Lens 36 is a SELFOC lens having a focal length of about 1.0 mm and is located at about 1.0 centimeters (cm) from mirror 20 and optical fiber 38 has a length of about 1.0 meters and is located with input-end 38A thereof at about 0.1 cm from lens 42.

Curves C1, C2, C3, C4 and C5 depict anticipated approximate combinations of feedback and reflectivity of emitting surface 16A of gain-structure which will result in respectively one, two, five, ten and twenty possible oscillating modes for laser 40. It should be noted that more than one possible mode of oscillation does not imply that laser 40 will operate in more than one mode simultaneously, but that the laser will be operating at any instant in any one of those possible modes but probably randomly "hopping" from one mode to the next with a resulting mode-noise or output-power fluctuation. The more the possible oscillating modes, the greater is likely to be the mode-noise. It may be found, in practice, that with wavelength selectivity selected for a given feedback level to permit less than about five possible modes, mode-noise can be reduced to a tolerable level.

It can seen from FIG. 6 that in order to arrive at a degree of selectivity such that there is only one possible operating mode, it may be necessary to raise the reflectivity of mirror 42 to about 0.8 or greater (80% or greater). This may cause OPS-structure 13 to be so wavelength selective that, because of manufacturing variations in deposition of mirror 42 on gain structure 16 or manufacturing variations in the thickness of gain-structure 16, it

is difficult to provide that the one possible mode is at the peak gain-frequency of the OPS structure.

It should also be noted that in cases where a resonator can be made to operate in any one mode by providing a high degree of selectivity, the mode frequency may change as a result of relatively small changes in properties of components, for example, a change in peak gain frequency of the OPS structure. This may be rectified by means of a feedback mechanism to counteract such a drift. By way of example, the temperature of the OPS structure could be actively controlled to control the peak gain-frequency as is commonly practiced in controlling the emitting wavelength of edge emitting diode-lasers used for optically-pumping solid-state lasers.

It can also be seen from FIG. 6, that a surface reflectivity about 0.40 may result in as few as five possible oscillation modes at relatively low feedback. A reflectivity of this magnitude could achieved by omitting the customary prior-art antireflection coating 18 of FIG. 1, whereby the Fresnel-reflection from emitting surface 16A of gain-structure 16 would serve as mirror 42. By way of example, in a semiconductor gain-structure 16 providing a peak gain at a wavelength of about 980 nm the outermost layer of the gain structure may be a layer of InGaP having a refractive index of about 3.2. This would provide a reflectivity of about 27%. To obtain any lower reflectivity of surface 16A would, of course require depositing a reflection reducing coating thereon.

The wavelength-selective arrangement of FIG. 6 may be used cooperatively with another wavelength-selective arrangement such as locating a wavelength selective device inside the resonator, or providing

that a resonator mirror is sufficiently wavelength-selective. Under these circumstances, the reflectivity of surface 16A is preferably between about 15% and 80%, where the lower value is that believed to be a minimum required for surface 16A to make a significant contribution to wavelength selectivity.

FIGS 7A, 7B and 7C depict arrangements for providing various reflectivity levels on emitting surface 16A of gain-structure 16. In each drawing, an outermost portion of gain-structure 16 includes active layers 60 separated by spacer layers 62, which, as is known in the art, can be a composite of two or more layers. Spacer layer 62 separates active layers 60 by an optical distance of one-half wavelength at the lasing wavelength. Typically such a gain-structure also includes an outermost barrier or electrical confinement layer 64 about one or more half wavelengths in optical thickness. The barrier layer has a higher bandgap than the spacer layers and serves to reduce migration of carriers away from the active layers. In this arrangement, emitting surface 16A of gain structure 16 is considered to be the outermost surface of confinement layer 64.

In the arrangement of FIG. 7A the customary antireflection layer 66 (indicated in phantom) of prior-art OPS structures has been omitted, such that the reflectivity of surface 16A is the Fresnel reflectivity of the semiconductor material of barrier layer 64. Depending on the particular material this may be between about 20% and 40%, corresponding to refractive indices of the material between about 2.5 and 4.0.

If the Fresnel reflection from an uncoated 16A is too high for the degree of selectivity desired,

the reflection may been reduced by a coating 68 of one or more layers as depicted in the arrangement of FIG. 7B. Here it should be noted that the objective of these layers is not to reduce the reflectivity to the minimum possible value as would be the case with a conventional antireflection coating, but may be used to reduce the reflection from the Fresnel value to as low as about 15%.

Referring to FIG. 7C, a higher reflectivity than the Fresnel reflectivity is provided by partially transmitting mirror 42 including alternating low refractive-index layers 72 and high refractive-index layers 74. The layers may be of dielectric materials or semiconductor materials transparent to the wavelength of laser radiation and ump-light radiation. There may be two or more layers. The design of such multilayer mirrors is well known in the art and, accordingly, is not discussed herein.

Referring to FIG. 8, another embodiment 50 of a laser in accordance with the present invention is illustrated. Laser 50 includes an OPS-structure 15 having a Bragg-mirror structure 14 and a semiconductor multilayer gain-structure 16. A laser resonator 24 is formed between Bragg-mirror structure 14 and an external mirror 22. Fundamental radiation F is focussed by lens 36 into optical fiber 38. Emitting surface 16A of gain structure is uncoated and provides a partially transmitting mirror on the surface of the gain-structure as discussed above for limiting the number of possible oscillating modes of laser 50. Optionally, a birefringent filter 52 is provided in laser-resonator 24. Birefringent filter 52 is arranged to provide additional selectivity in laser-resonator 24 for further reducing the number of oscillating modes of laser 50. The birefringent

filter can be selectively rotated, as indicated by arrows G, for selecting a preferred output wavelength for fundamental radiation F (within a range Another wavelength-selective element such as an etalon, a prism, a grating or a multilayer bandpass-filter may be used in place of birefringent filter 52.

Those skilled in the art will recognize from the discussion presented above that the arrangements of lasers 40 and 50 are not the only such arrangements that can provide sufficient laser-resonator wavelength-selectivity for suppressing mode-noise when output of the lasers is coupled into an optical fiber. One possible arrangement includes a laser resonator in which the OPS-structure is antireflection coated and wavelength-selectivity is provided entirely by a separate intracavity wavelength selective element. Another, non-exhaustive, possible arrangement includes providing that partially transmitting reflective coating 23 on mirror 22 has a reflection bandwidth narrower than the gain-bandwidth of gain-structure 16, such that mirror 22 functions as a wavelength-selective element in the context of this description. Such a narrow-reflection-bandwidth mirror may be used alone or in combination with other wavelength selective elements or devices discussed above.

The above exemplified and any other such combinations of wavelength selective elements or devices may be used for suppressing feedback mode-noise without departing from the spirit and scope of the present invention. Selection of suitable wavelength-selective elements will depend, inter alia, on such factors as the cost of manufacture, ease of incorporation into a laser resonator, and losses induced in the resonator by the elements.

It should be noted here that the feedback mode-noise suppression techniques of the present invention have been described with reference to a relatively simple, straight resonator configuration. Those skilled in the art will recognize that techniques described and depicted herein are not limited to the resonator configurations of lasers 40 and 50 but may be applied to any fundamental OPS-laser configuration.

The present invention has been described and depicted in terms of a preferred and other embodiments. The invention is not limited, however, to the embodiments described and depicted. Rather, the invention is defined by the claims appended hereto.

WHAT IS CLAIMED IS:

1. A laser, comprising:

a monolithic multilayer OPS-structure including a semiconductor multilayer surface-emitting gain-structure having an emitting surface, said gain-structure including a plurality of active layers spaced-apart by spacer layers and arranged to provide optical gain in said laser resonant-cavity, said optical gain occurring within a gain bandwidth characteristic of the composition of said gain-structure;

a laser resonant-cavity being terminated by first and second mirrors, said laser resonant-cavity configured to include said gain-structure of said OPS-structure; and

a pump-radiation source arranged to deliver pump-radiation to said gain-structure for generating laser-radiation in said laser resonant-cavity and wherein said emitting-surface of said gain structure has a reflectivity between about 15 and 80 percent whereby mode-noise from optical feedback into the resonant-cavity is minimized.

2. The laser of claim 1, wherein the outermost layer of said gain structure has a refractive index for said laser radiation greater than about 2.5.

3. The laser of claim 1, wherein a partially-transmitting reflective coating surmounts an outermost layer of said gain-structure.

4. The laser of claim 3, wherein said partially transmitting reflective coating includes

one or more layers of a dielectric material.

5. The laser of claim 3, wherein said partially transmitting reflective coating includes one or more layers of a semiconductor material.

6. The laser of claim 1, wherein a reflection reducing coating surmounts an outermost layer of said gain-structure.

7. The laser of claim 1, further including a wavelength selective element located in said resonant cavity, said frequency-selective element being selected from the group consisting of a prism, a grating, a solid-etalon, multilayer interference filter, and a birefringent filter.

8. A laser system, comprising:

an OPS-laser arranged to deliver output radiation therefrom said OPS-laser includes a semiconductor multilayer surface-emitting gain-structure having an emitting surface, said gain-structure including a plurality of active layers spaced-apart by spacer layers and arranged to provide optical gain in said laser resonant-cavity, said optical gain occurring within a gain bandwidth characteristic of the composition of said gain-structure;

an optical fiber for transporting said output radiation to a delivery location, said optical fiber having an input end and an output end; and

an optical arrangement for directing said output radiation into said input end of said optical fiber, and wherein said emitting-surface

of said gain structure has a reflectivity between about 15 and 80 percent whereby mode-noise resulting from optical feedback of radiation reflected from the optical fiber is minimized.

9. The laser of claim 8, wherein said gain-structure has an outermost layer having a refractive index for said laser radiation greater than about 2.5.

10. The laser of claim 9, wherein a partially-transmitting reflective coating surmounts an outermost layer of said gain-structure.

11. The laser of claim 10, wherein said partially transmitting reflective coating includes one or more layers of a dielectric material.

12. The laser of claim 10, wherein said partially transmitting reflective coating includes one or more layers of a semiconductor material.

13. The laser of claim 8, wherein a reflection reducing coating surmounts an outermost layer of said gain-structure.

14. The laser of claim 8, further including a wavelength selective element located in said resonant cavity, said frequency-selective element being selected from the group consisting of a prism, a grating, a solid-etalon, multilayer interference filter, and a birefringent filter.

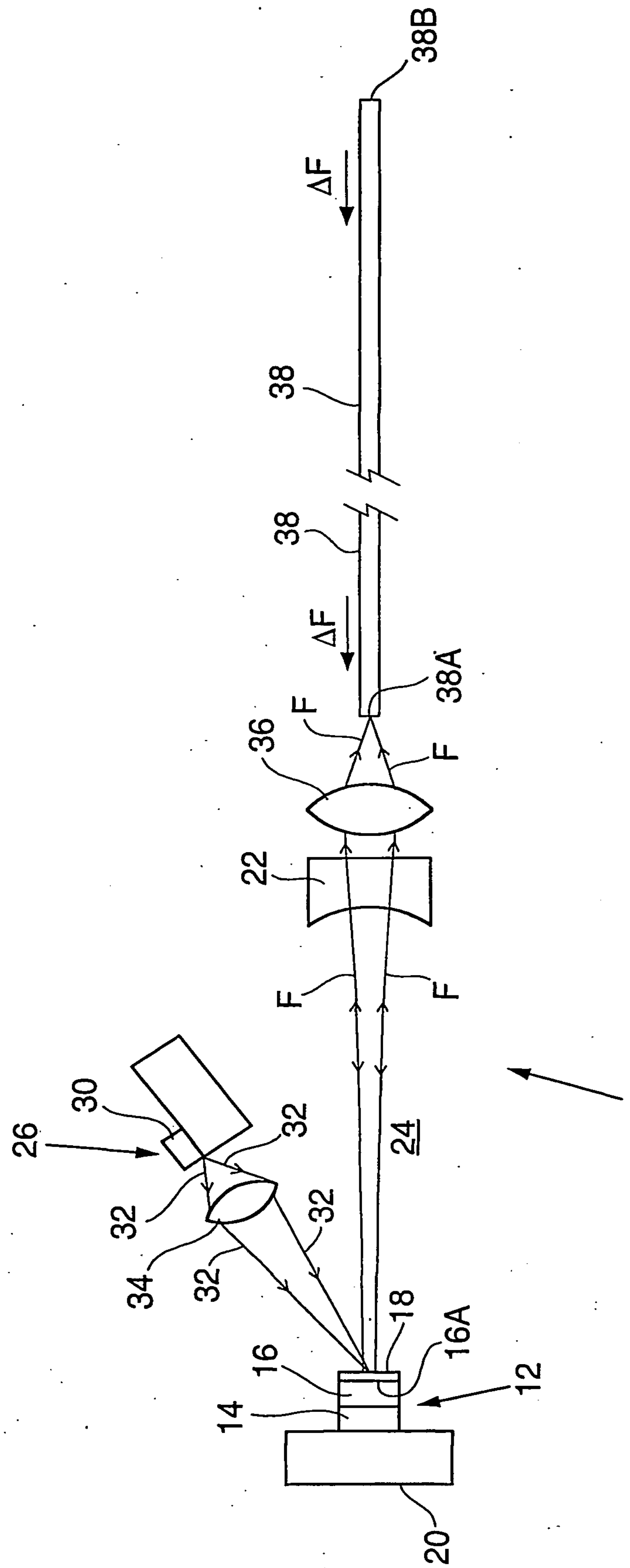
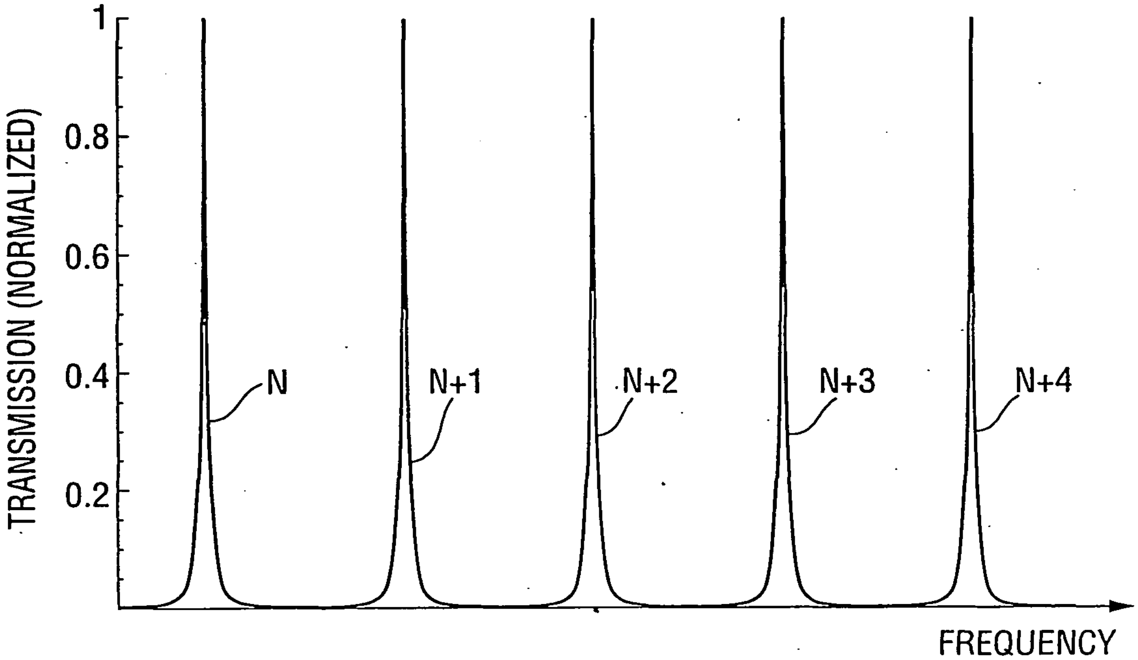


FIG. 1
(PRIOR ART)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N+3
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FREQUENCY

FIG. 2

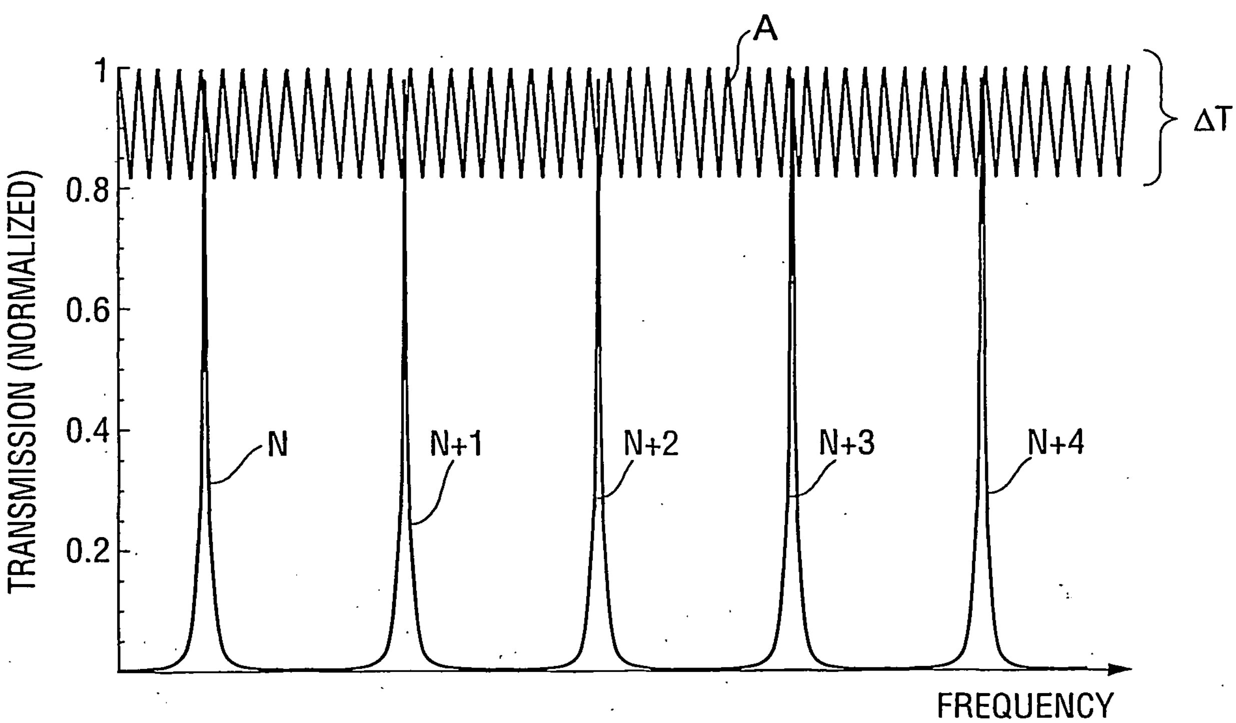
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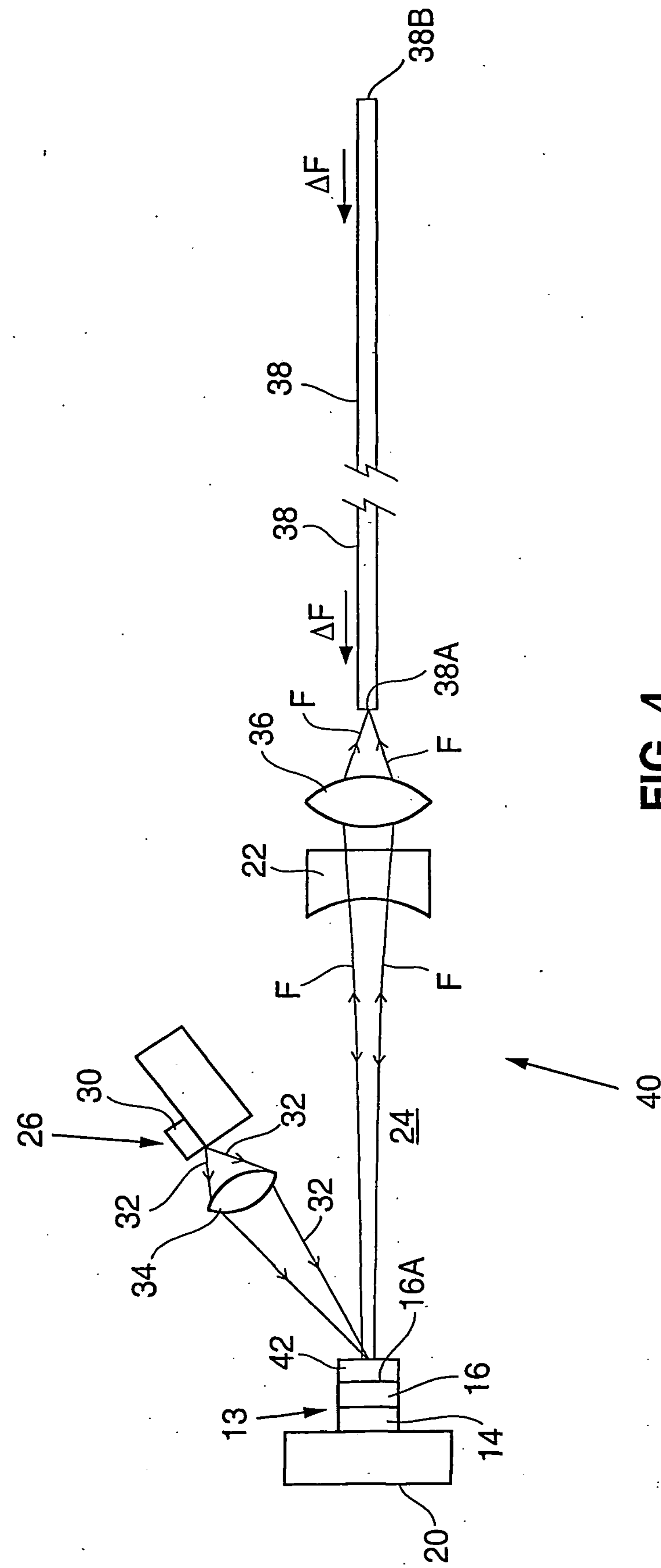
FIG. 3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16A
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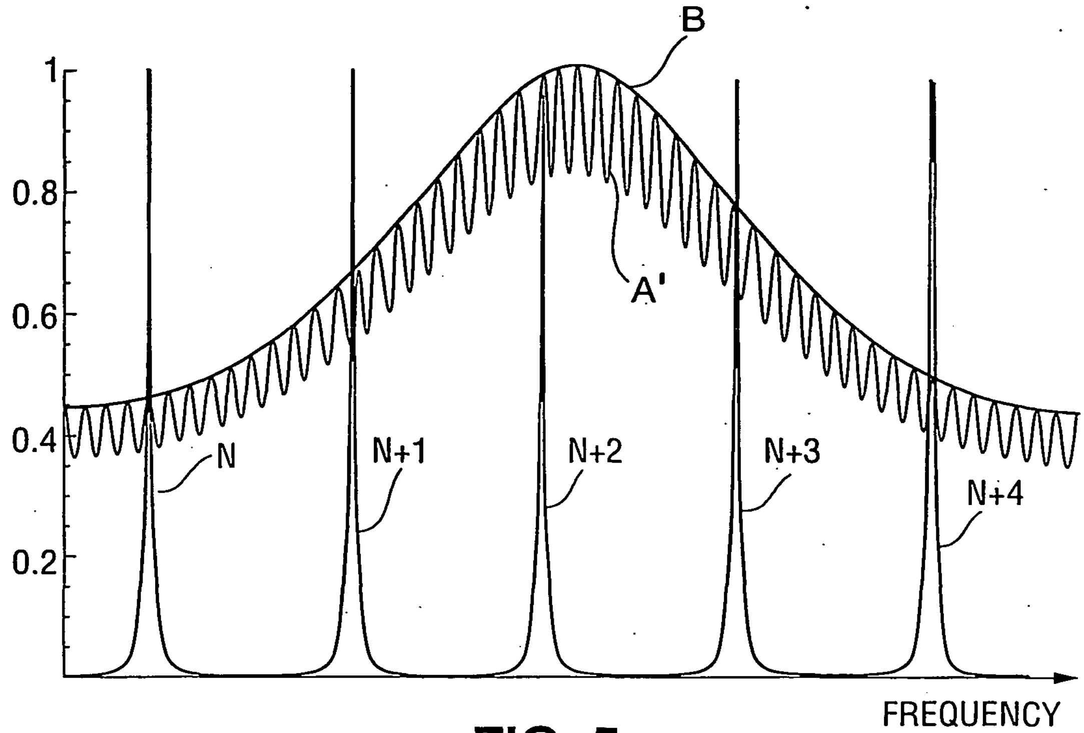
FIG. 4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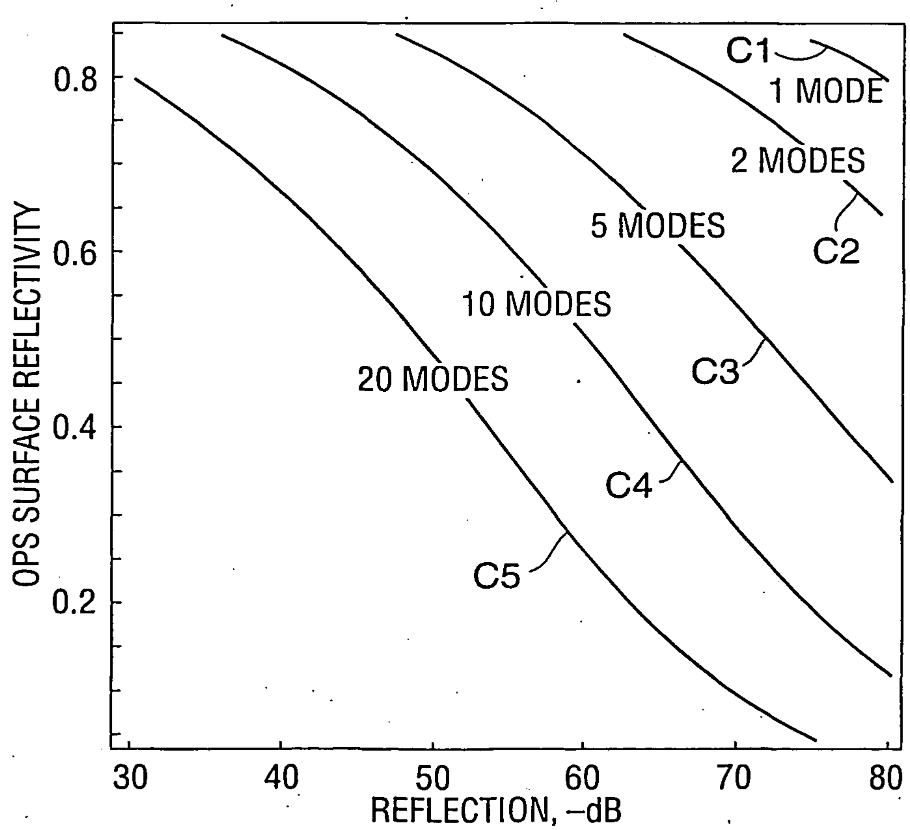
FREQUENCY

FIG. 5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0.6
0.4
0.2
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2 MODES
C2
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C3
20 MODES
C4
C5
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50
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70
80
REFLECTION, –dB

FIG. 6

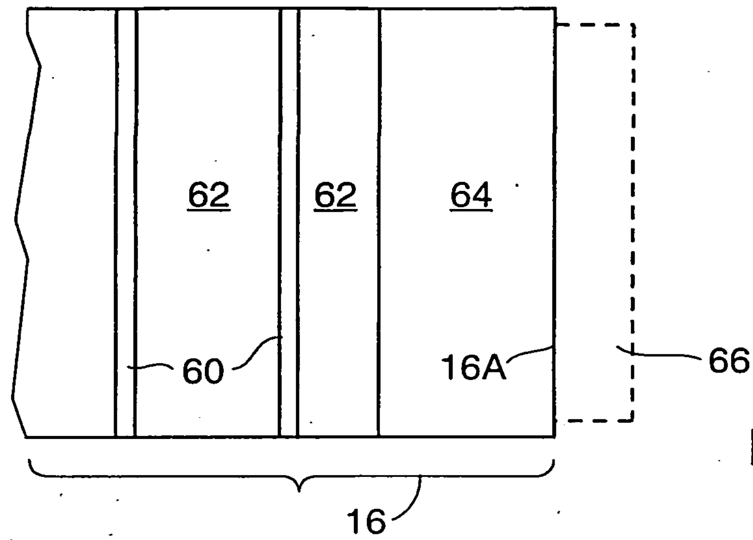

FIG. 7A

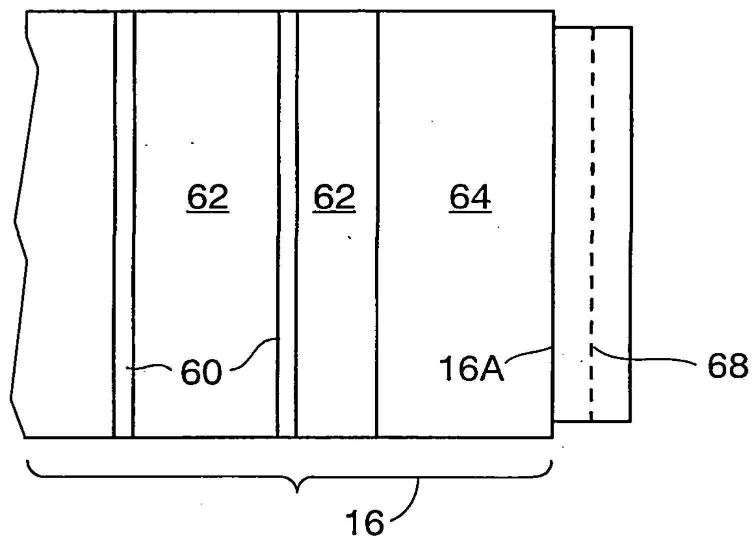

FIG. 7B

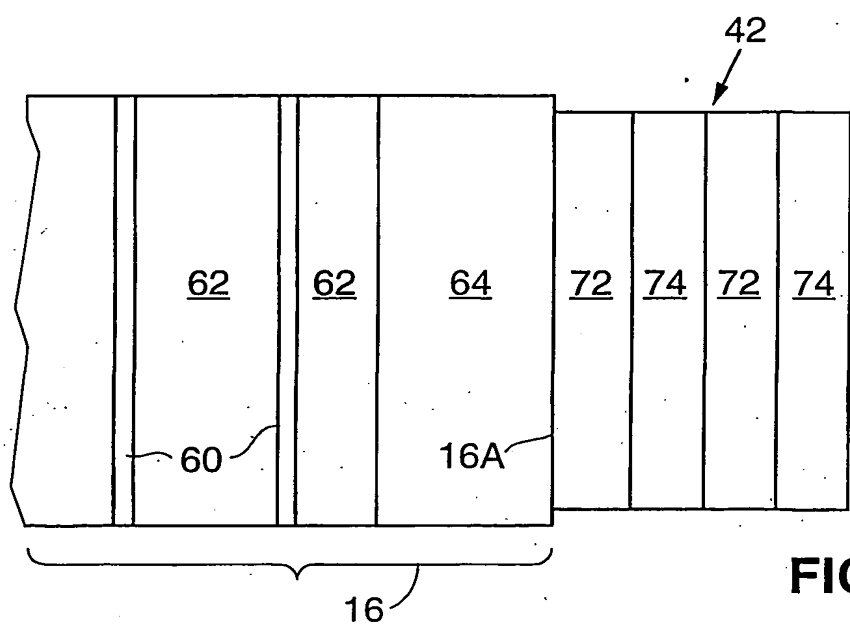

FIG. 7C

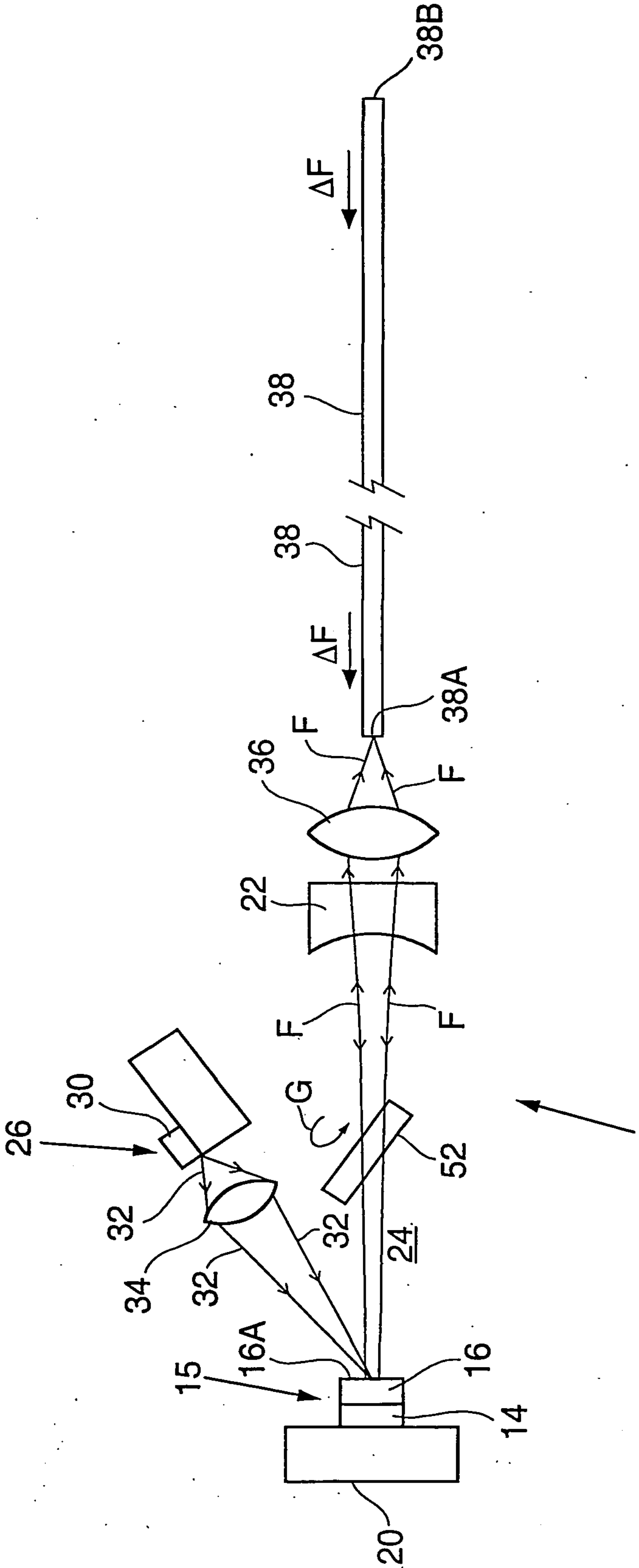
38B
ΔF
38
38
ΔF
38A
F
36
F
22
F
F
G
30
26
52
50
32
32
24
34
32
16A
15
16
14
20

FIG. 8